MASTER Conf-791203--9

SAND79-1743C

LOW ENERGY ION EROSION STUDIES OF MACHINE FACETED STAINLESS STEEL*

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ABSTRACT

Type 304 annealed stainless steel substrates with a variety of machine faceted surface finishes have been eroded by low energy (250-1000 eV) hydrogen, and argon ion beams. The dimensions of the machine faceted features studied range from that of the annealed crystalline grain size (approximately 0.0125 cm) to 0.25 cm macro-structures. Relative erosion rates have been measured and analysed as a separable function of angular dependent sputtered particle emission and particle recapture. It was found that the formation of a faceted topography on the surface of components exposed to low energy, light-ion erosion can significantly reduce the effective ion erosion yield.

*This work is supported by the Office of Fusion Energy, U.S. Department of Energy (DOE), under Contract DE-AC04-76DP00789.

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INTRODUCTION

The containment and manipulation of plasmas and ions is becoming an increasingly more important subject of concern in defense, energy,[1,2] home entertainment,[3] and microelectronics processing[4,5] technologies. In designing system components that are to be exposed to plasmas and ions it is usually desirable and sometimes necessary to choose materials and designs that minimize ion erosion.

In association with the development of magnetically confined fusion reactors such as Tokamaks, much work has been done involving the development of component materials and designs that can withstand the flux of hydrogen and helium ions that bombard the surfaces of internal Tokamak components. Stainless steel is being used as a material for the fabrication of internal Tokamak components.[1,2] Borders et.al.,[6] Roth et al.,[7] and Smith[8] have measured hydrogen ion erosion of flat stainless steel samples. Texturing the surface of a material to increase resistance to ion erosion has been proposed. Cramer and Oblow[9] have made calculations based on computer modeling several optional sputtering reaction mechanisms for a hypothetical

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surface honeycombed by an array of holes characterized by a hole depth-to-width aspect ratio. Their calculations suggest a significant improvement in resistance to ion erosion can be gained by forming such a honeycombed surface. This improvement has been observed experimentally by Yoshikawa,[10] and Abe et al.,[11] for polyenergetic, multi-directional hydrogen plasmas on honeycombed molybdenum surfaces.

Honeycombed structures are a rather special, limited subset of surface features that can be formed. It would be advantageous to understand in general how surface topography can effect erosion yield, from the standpoint of offering engineering design options, and also from the standpoint of providing information about the basic dynamics of sputtering phenomenon. A more general class of surface topographies can be described in terms of faceted, sawtooth structures. Such surface structures can be stamped onto sheet metal stock during manufacturing, or machined during fabrication processes. The study of the ion erosion yields associated with such surface features gives basic physical insight about the angular dependency of sputtering events. Littmark and Hofer[12] have derived equations describing sputtering from faceted surfaces. Their equations are based on the presumption that the trajectories of the sputtered particles can be described by a spherically symmetric cosine function and a sticking coefficient equal to unity; the resultant expressions predict an increase in the erosion yield from a faceted surface. Other well established experimental results[7,13,14] involving special types of faceted surfaces indicate both increases and decreases in the ion erosion yields.

The current work presents the results of the first systematic study of the ion erosion characteristics of machined faceted surface structures compared to flat surfaces. Type 304 annealed stainless steel (effective atomic mass = 54.61) was used for fabricating samples. Both hydrogen (Atomic mass = 1) and argon (Atomic mass = 40) ion erosion characteristics have been studied as a function of ion energies from 250 eV to 1000 eV. The goals of this study are 1) to obtain engineering evaluation information for the optimization of components exposed to ion bombardment, and 2) to gain insight toward the basic physical mechanisms involved in sputtering.

EXPERIMENTAL

A Kaufman ion source (Veeco Microetch System) was characterized for use with hydrogen[15] and used to obtain a relatively high density, collimated, uniform ion beam over a large target area thereby permitting simultaneous erosion rate determinations of large numbers of samples. Unlike sputter yield determinations in which mono - energetic, single mass/charge species ion beams are employed to obtain absolute physical sputtering yields, the beams used in this study were polyenergetic, and contained both atomic and molecular hydrogen ions. The ions were extracted from the ionization chamber into the target chamber as an ion beam by applying a positive acceleration potential (250, 500, or 1000 V) which determined the upper energy limit of ions in the beam. The erosion yield (defined as the number of atoms lost by the target material for each bombarding ion) was calculated from the weight lost by a sample, and the total bombarding ion dose indicated by Faraday cup readings of the current density at each target sample position.

Table 1 gives the dimensions and the topographies of the machine faceted surfaces studied. The dimensions of the single V-groove microstructures are of the same order of magnitude as the crystalline grain sizes in type 304 annealed stainless steel. In addition, typical 8 to 32 microinch flat surface finishes resulting from electropolishing, mechanical polishing, or grinding the stainless steel samples were studied. During an erosion run the samples were fitted into nickel foil boxes so that only one surface was exposed to the ion beam. The samples were then placed on an array of angle blocks, or at normal incidence with respect to the ion beam on the water cooled target platform. Hydrogen erosion yields were measured after a dose of typically 10^{21} ions/cm^2 which corresponded to approximately one week of ion exposure time. Argon erosion yields were measured at typical dose levels of 10^{20} ions/cm^2 which could be accumulated in approximately 4 hrs. of exposure time.

RESULTS AND DISCUSSION

Figures 1-5 show the results. The ordinates of all of the graphs represent <u>relative</u> erosion yield. ~~which~~ This is the erosion yield observed for a surface at a particular angle of incidence divided by the maximum erosion yield measured for all sample surface conditions for all angles of ion beam incidence for a given acceleration potential setting, for hydrogen and for argon. The curves on the graphs represent a least-squares fit of the experimental data. The erosion yield as a function of (nominal) surface angle was measured for seven different angles. The erosion yield as a function of facet angle was measured for the three angles used for machining the faceted topologies; these results were extrapolated to physically realistic limits[9] at 0^{o} and 90^{o}. The relative erosion yields shown were reproducible to within 10%; such a reproducibility limit is typical of the measurements of other groups observing light ion erosion of metal alloys.[16]

Figure 1 shows, for 250 V and 1000 V accelerated hydrogen beams, the relative erosion yield of the flat pieces as a function of surface angle compared to the relative erosion yield as a function of the angle the ion beam makes with the individual faceted surface structures for the three types of machined surface topographies studied. There is little difference in the hydrogen ion erosion characteristics observed for macro double V-grooves compared to macro or micro single V-grooves. Resistance to ion erosion increases for more acutely angled facets. The similarity in the erosion characteristics observed for the three different topologies, and the large difference between the curve for the flat samples and the curves for the machined samples indicate that forward sputtering of particles in combination with particle recapture plays an important role in determining the effective erosion yield of faceted surfaces for 250-1000 eV hydrogen ions.

Figure 2 shows relative erosion yield vs. surface angle for 250, 500, and 1000 V hydrogen ion beams for the flat 32 microinch samples compared to the 45^{o} double V-groove samples. The shift in the angle at which a maximum erosion yield is observed as a function of ion energy agrees qualitatively with Lindhard's first principles formula,[17] which predicts that the angle should decrease for increasing ion energy, or for decreasing the atomic number of the bombarding ions or the target sample. The data presented in Fig. 2 illustrates that a significant improvement in resistance to low energy hydrogen ion erosion can be obtained by machining facets on exposed surfaces.

Figure 3 shows the relative erosion yields resulting from 250 V and 1000 V argon ions on the flat substrates compared to the three machined topographies. The difference in the yields associated with the macro V-groove samples compared to the micro V-groove samples for argon compared to hydrogen can be interpreted as indicating that a smaller component of forward sputtering occurs for argon ions compared to hydrogen ions. The increase in the relative erosion yields of the faceted samples for 1000 V argon compared to 250 V argon ions can be interpreted as indicating that the component of forward sputtering is smaller at higher ion energies. These results are consistent with the classical dynamics law that heavier particles, i.e. the argon ions, carry away more forward momentum from a collision. However, enough forward sputtering and recapture occur for the argon ion energies observed that some increased resistance to ion erosion can be obtained by faceting exposed metal surfaces.

Figure 4 is analogous to Fig. 2 for argon ions. No change in the surface angle associated with maximum erosion yield as a function of energy is observed within the limits of the experiment; however, a shift in angle may be contained within the general broadening of the line shapes describing sputtering by the higher energy argon ions. The data displayed in Fig. 4 reaffirms the resistance to low energy ion erosion exhibited by faceted surfaces.

Figure 5 shows a stylus instrument profile of 8 microinch and 32 microinch surface finishes on the flat 304 stainless steel samples before and after bombardment by 10^{21} ions/cm^2, 1000 V hydrogen. The surface roughening after ion bombardment can be associated with differential sputtering of various grain orientations in 304 annealed stainless steel. There is little difference in the erosion yields observed for 32 microinch ground surface finishes and 8 microinch polished finishes; both ground and polished surfaces approach the same degree of roughening under ion bombardment. No difference in erosion yield as a function of ion dose was observed for hydrogen ion doses less than the maximum dose of 10^{21} ions/cm^2. The degree of surface roughening observed in Fig. 5d and e is apparently stable under ion bombardment within this dose range. The average aspect ratio of these surface features is approximately equal to 0.025 which is below the value associated with a significant change in the erosion yield reported by the groups[9,10,11] studying honeycombed structures.

Similar surface profiles are observed for stainless steel surfaces after argon ion bombardment.

CONCLUSIONS

Forming faceted structures on the surface of stainless steel components that are to be exposed to low energy ion bombardment with atomic masses from 1 to 40 can significantly increase the components' resistance to the effect of ion erosion. The particles emitted by such an ion environment are predominantly sputtered in forward direction. The forward sputtering component decreases for a primary beam with a higher atomic mass and/or greater ion energies.

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CAPTIONS

Table 1. Topologies and dimensions of the machine faceted 304 annealed stainless samples used in this study. The average grain size of the crystallites in the samples was of the order of the micro single V-groove samples: 0.0125 cm. Eight microinch electropolished, diamond polished, and thirty-two microinch ground "flat" surface finishes were also studied.

Figure 1. Relative erosion yield vs. the ion beam angle for 250 and 1000 V accelerated hydrogen beams. The dashed lines represent the yields observed for the 32 microinch "flat" samples placed on angle blocks. The dash-dotted lines represent the yields observed for the faceted samples as a function of the angle of the ion beam with the facet surface. The similarity of the yields observed for micro and the macro single V-groove samples indicates that forward sputtering predominates. The difference between the yields observed for the faceted samples, and the yields observed for the flat samples at a given angle indicate secondary particle recapture plays a dominant role in determining the effective erosion yield of the faceted samples.

Figure 2. Relative erosion yield vs. the ion beam angle with respect to the surface of the flat samples and the nominal surface of the 45° double V-groove samples for 250, 500, and 1000 V hydrogen beams. A significant increase in resistance to erosion yield can be gained by

faceting surfaces exposed to ion erosion. The erosion yield for a 250 V hydrogen ion beam impinging at an angle of 55° (the calculated angle of incidence mode for a Tokamak reactor)[7] on the faceted surface is reduced to about 15% of the value observed for the flat surface.

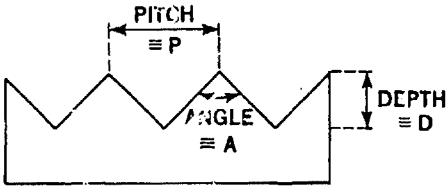
Figure 3. Relative erosion yield vs. ion beam angle for 250 V and 1000 V accelerated argon beams. This graph for argon is analogous to Fig. 1 for hydrogen. The difference observed in the yields associated with the macro compared to the micro single V-groove samples indicates a smaller component of forward sputtering occurs for argon compared to hydrogen. The proximity of the curves describing the yields from the faceted surfaces to the curve for the yield from the flat surface for 250 V compared to 1000 V argon indicates that forward sputtering with sputtered particle recapture occurs more frequently for 250 V argon than for 1000 V argon.

Figure 4. Relative erosion yield vs. the ion beam angle with respect to the "flat" surface and the nominal 45° double V-groove faceted surface for argon. A considerable increase in resistance to argon ion erosion can be gained by faceting metal surfaces, especially for lower energy argon ions.

Figure 5. Stylus instrument profiles of ground or polished stainless steel surfaces before and after ion bombardment.

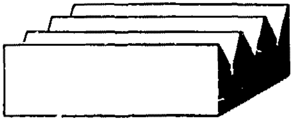
The surfaces acquire the same degree of roughness which appears to be stable independent of ion dose. The aspect ratio associated with the ion bombarded surfaces is too small to significantly change the erosion yield from that of an unbombarded flat surface.

MACHINED SURFACE STRUCTURES



MACRO	(MILLING MACHINE)		
SIZE	A	P	D
.25 x .50"	45°	.041"	.040"
.25 x .50"	60°	.058"	.046"
.30 x .50"	90°	.100"	.045"

MICRO	(LATHE)		
SIZE	A	P	D
.25 x .35"	45°	.007"	.005"
.25 x .35"	60°	.010"	.005"
.25 x .35"	90°	.013"	.005"



SINGLE V-GROOVES

MACRO	(MILLING MACHINE)		
SIZE	A	P	D
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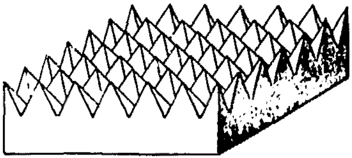
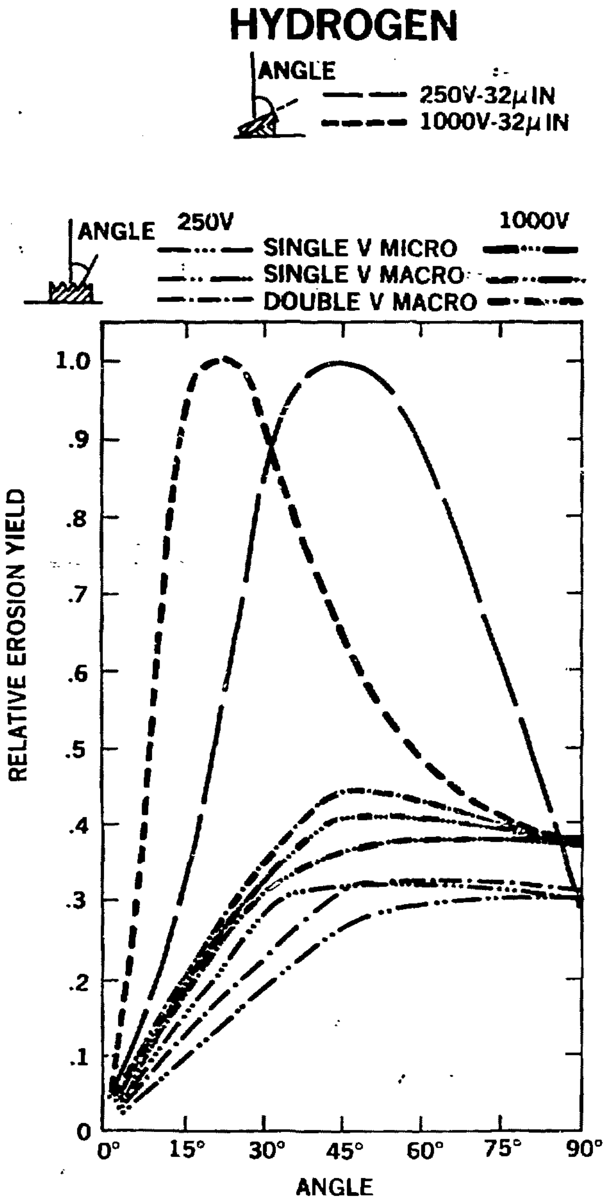
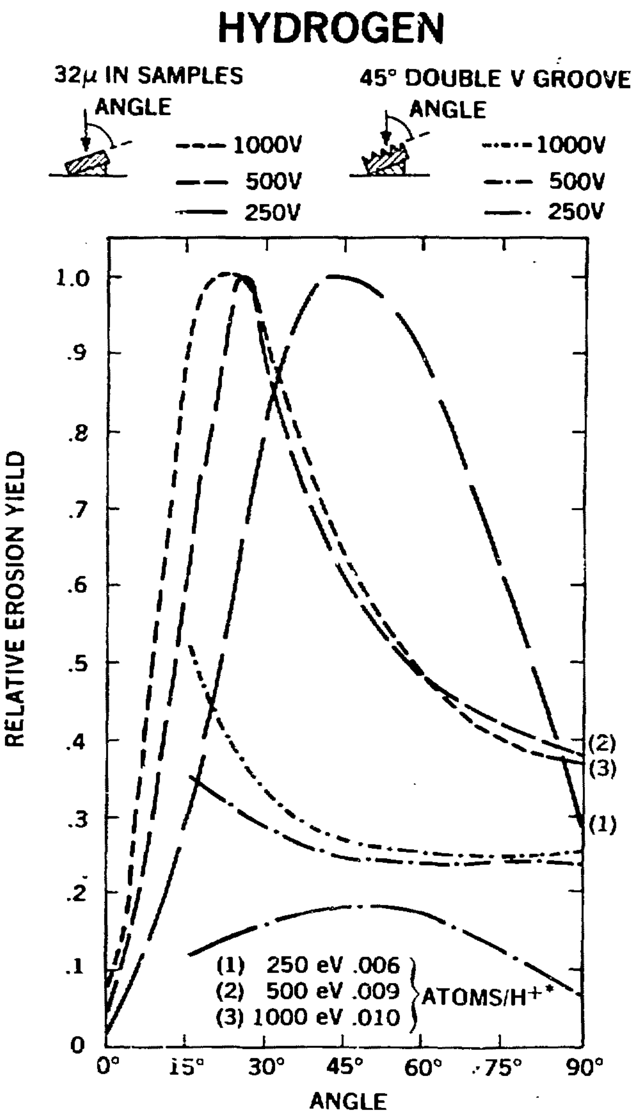
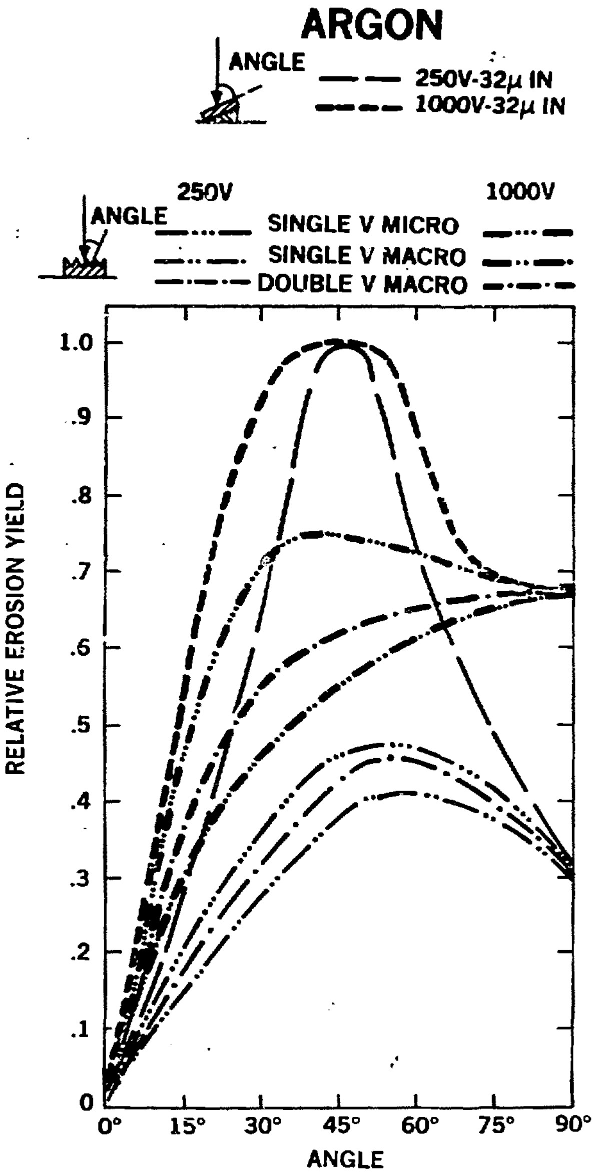
.46 x .46"	60°	.058"	.040"
.50 x .50"	90°	.100"	.040"



DOUBLE V-GROOVES


HYDROGEN
ANGLE
250V-32μIN
1000V-32μIN
ANGLE
250V
1000V
SINGLE V MICRO
SINGLE V MACRO
DOUBLE V MACRO
RELATIVE EROSION YIELD
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
0°
15°
30°
45°
60°
75°
90°
ANGLE


HYDROGEN
32μ IN SAMPLES
ANGLE
1000V
500V
250V
45° DOUBLE V GROOVE
ANGLE
1000V
500V
250V
RELATIVE EROSION YIELD
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
0°
15°
30°
45°
60°
75°
90°
ANGLE
(2)
(3)
(1)
(1) 250 eV .006
(2) 500 eV .009
(3) 1000 eV .010
ATOMS/H+*


ARGON
ANGLE
250V-32μ IN
1000V-32μ IN
250V
1000V
ANGLE
SINGLE V MICRO
SINGLE V MACRO
DOUBLE V MACRO
1.0
.9
.8
.7
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75°
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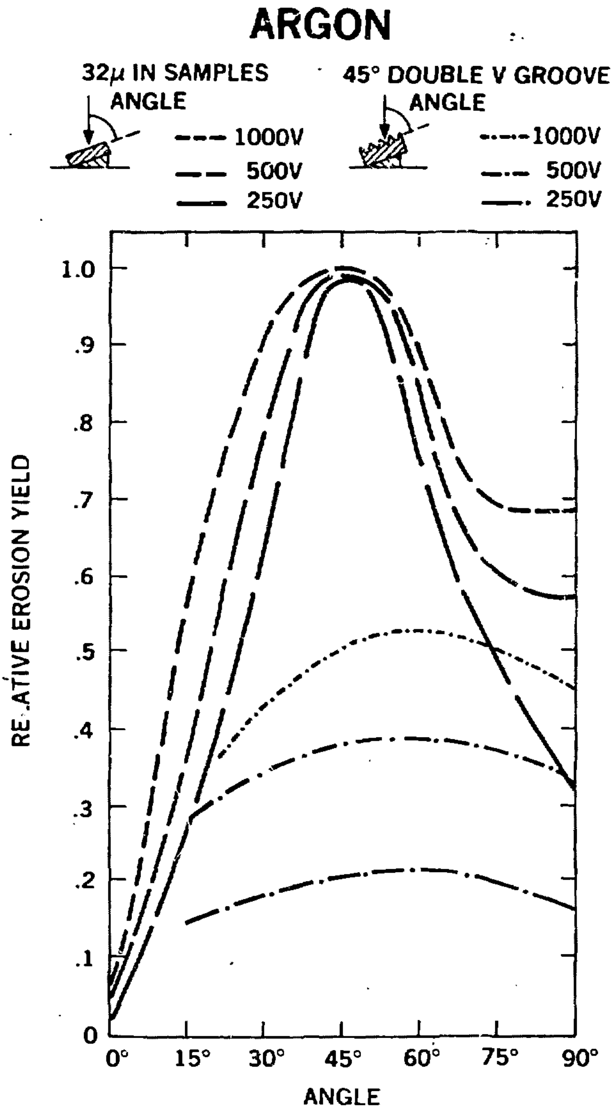
RELATIVE EROSION YIELD
ANGLE


ARGON
32μ IN SAMPLES
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45° DOUBLE V GROOVE
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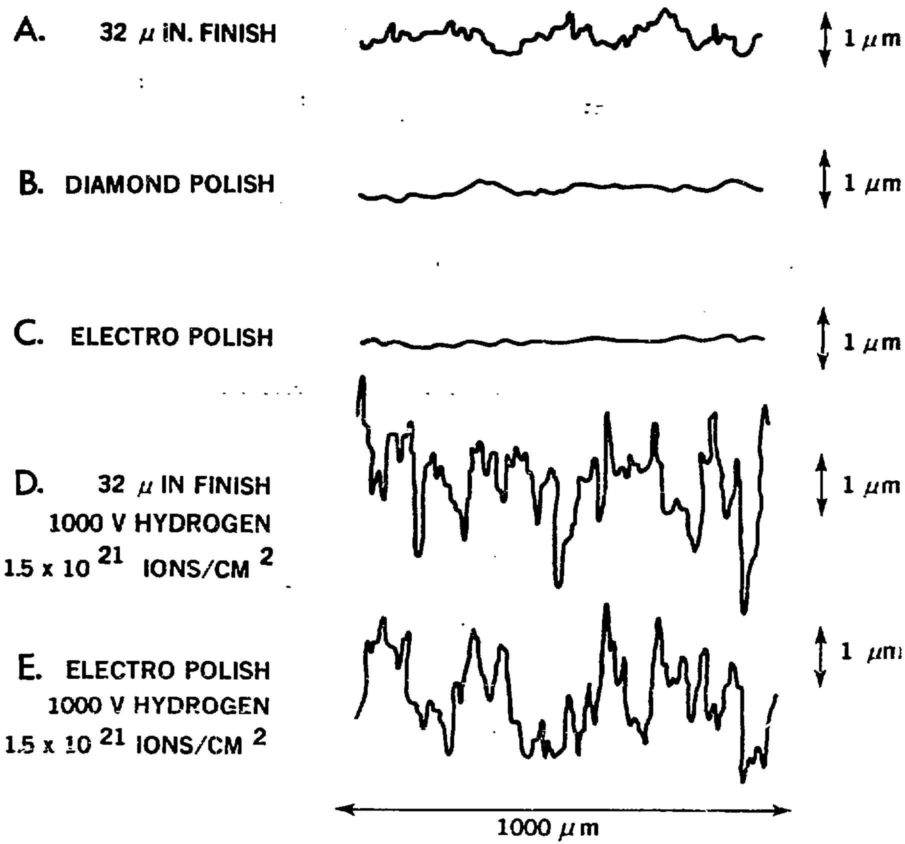
ANGLE



304 SS SURFACE TOPOGRAPHY